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13. ABSTRACT (Maximum 200 words)

**Abstract**

We explore the feasibility of plasma instabilities in quantum well structures with the aim of developing compact, coherent THz radiation sources, by introducing and studying specific structures which could lead to experimental verification of current driven plasma instabilities, and ensuing THz radiation. A fully self-consistent formalism was developed to determine the non-equilibrium steady state under bias. Determination of the non-equilibrium steady state provides the I-V curves and the plasma response. These are in good agreement with experiments carried out at TU Vienna. A sharp emission line was obtained in the most recent structure, suggesting that we are close to the onset of plasma instability. Effects of magnetic field on the electron-electron scattering rate was studied theoretically, and experimentally verified, providing a diagnostic tool for the relative strength of two- electron, vs. one-electron scattering processes. A new connection was established with an experimental group at UC Santa Barbara, to obtain an independent proof of principle of the plasma instability phenomenon in a THz pumped quantum well structure.

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# Plasma Instability Based
# Compact Coherent Terahertz Radiation Sources.

## Final Progress Report

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## I. Introduction

The main goal of this program is to explore the feasibility of plasma instabilities in low dimensional semiconductor systems, leading to compact, coherent, terahertz (THz) radiation sources. In this program we have introduced and studied systems, which could lead to experimental verification of current driven plasma instabilities (CDPI) in lower dimensional solid state systems.

Our theoretical effort is supplemented by an interactive program for experimental verification of our results, at the Institute for Solid State Electronics of the Technical University of Vienna, Austria.

In addition, quite recently, we have also begun an interaction with an experimental group at the University of California at Santa Barbara, to obtain an independent proof of principle of the plasma instability phenomenon in a terahertz pumped quantum well structure.

Several papers have been published based on the work in this program. This work also led to several other presentations, including invited papers at international conferences.

The theoretical developments during this project, and the experimental results to date which already confirm our results, suggest that the main goal of this program, viz. the generation of (a) plasma instabilities, and (b) the ensuing electromagnetic radiation in the THz range may be realized in the near future.

Section II provides a statement of the problems studied, section III summarizes the most important results and the last section lists the publications, and the participating scientific personnel.

## II. Statement of the Problem

There has been a great deal of interest in and need for compact, coherent and tunable sources of terahertz (THz) radiation, in view of their many possible applications. In terms of previous approaches, the conventional electronic devices (transistors, IMPATT diodes etc.) cannot reach this frequency range due to the so called impedance limitation. The quantum cascade laser approach has been extended to THz frequencies just recently. We have proposed stimulated generation of plasmons (plasma instabilities) as a novel way to generate THz radiation. The microcharge oscillations of such plasmons can become the source of electromagnetic radiation in the THz range. This is a robust phenomenon, since the micro charge oscillations induced by a plasma instability are intrinsically coherent. Analogs of this phenomenon are well known in gaseous plasmas, where plasma instabilities

have been studied theoretically and observed experimentally in many situations and have led to device applications. Even at high temperatures and in spite of various scattering effects, these coherent collective oscillations are not easily disrupted. Typical plasma oscillations of the carriers in low dimensional semiconductor systems are in the THz range. We have therefore systematically investigated the possibility of generating plasma instabilities in several such systems.

That nonequilibrium plasmas can spontaneously develop growing plasma oscillations (plasma instabilities) under suitable conditions, is due to the basic fact that plasmons constitute a natural energy transfer channel in a plasma, and provide an easy way to relax the excess free energy of a nonequilibrium plasma. A sufficiently strong population inversion in the carrier distribution is needed for this to happen. Such a population inversion can often be achieved by driving a current through the plasma. However, the drift velocity required to achieve such a population inversion in uniform solid state plasmas is prohibitively large, of the order of the Fermi velocity. Introducting a periodic density modulation in a high mobility quantum wire, leads to a dramatic reduction in the threshold drift velocity required to generate a plasma instability, and such a system remains a suitable candidate for experimental verification of this phenomenon. Bounded plasmas, especially in the form of quantum well structures, offer distinct advantages, and can be employed as active media to generate strong plasma instabilities by selective extraction and injection of carriers.

Observation of decaying plasmons in solid state systems has now been reported. Radiative decays of plasmons from two-dimensional electron channels and parabolic quantum wells have been observed, emitting radiation in THz regime at low temperature. Emission from coherent (but decaying) plasmon oscillations has been observed even at room temperature, and in the presence of bulk doping, on a picosecond time scale. These results suggest that plasma oscillations can survive even at room temperature in semiconductor systems. Thus, generating a plasma instability according to our ideas mentioned above could provide the means to *sustain* coherent plasma oscillations and the ensuing radiation, if the instability is strong enough to overcome the loss mechanism. This phenomenon can thus be used for the realization of practical semiconductor THz radiation sources, in various parameter domains.

In our present work we have developed a fully self-consistent formalism, to determine the non-equilibrium steady state (NESS) of a quantum well structure under bias. We have determined the I-V characteristics for such structures, and also the plasma response arising from such a structure, as a function of bias. Based on this theoretical work, specific quantum well structures were then grown and characterized. Population inversion

was achieved under bias, as evidenced by emission of THz radiation. In the latest series of structures, a very sharp line was observed, and this suggests that the condition for plasma instability based, self-sustaining radiation source may not be too far away.

## III. Main Results.

There were 6 major topics covered in this program. We summarize below the main results:

### 1. Fully self-consistent formalism.

A fully self-consistent computational scheme for obtaining the non-equilibrium steady state (NESS) for various quantum wells under bias has been developed. The eigenstates of the quantum well structure are determined by the Schroedinger-Poisson scheme, and the subband populations are determined by rate balance equations for each subband. These balance equations require various transport rates. The inter-subband transfer rates via electron-electron interactions are obtained through a RPA self-energy calculation, the inter-subband electron-LO phonon transfer rates through a matrix elements approach, and the injection-extraction rates are obtained by determining the transfer matrix for the structure for complex energies. These three rate calculations are described in detail as topic 2 below. The self-consistent solution at any given bias is obtained when the input subband populations used for determining the non-equilibrium steady state agree with the output populations obtained through the rate balance equations. The details of this program are given in a Physica E paper (Ref. 1), and more fully in Feng's Thesis (Ref. 2)

Determination of the NESS provides the I-V curves, and the plasma response. These are compared with experiments (see topic 3, below).

### 2. Formalisms for various transport rates

*a. Generalized RPA formalism for inter-subband electron-electron scattering.*

We have developed a comprehensive formalism for inter-subband scattering due to the electron-electron interactions, based on the calculation of the self-energy of the carriers in the system under RPA. It can be shown that the so-called Auger process constitutes only the first bubble diagram in an infinite series which is summable under RPA. This formalism

properly takes into account all the inter-subband transitions involving carrier-carrier interactions, including collective effects involving plasmon creation and absorption. The formalism was initially developed for zero temperature, and then generalized for finite temperature equilibrium systems, using Matsubara formalism. The latter formulation was further generalized to non-equilibrium distributions.

This work has been published in Physica E (Ref. 3) and Physical Review B (Ref. 4).

*b. Formalism for inter-subband electron-LO phonon scattering rates for quantum well systems.*

While the electron-LO phonon scattering formalism for bulk system is textbook material, it requires appropriate adaptation for quantum well structures (systems confined in one dimension by arbitrary potential, and open in the other two dimensions). This has been carried out, and cast in a computable form for arbitrary quantum well structures. The main finding is that the electron-LO phonon scattering rates depend very sensitively on the shape and asymmetry of the quantum well structure. Due to phase space limitations, these rates are much lower than for bulk material.

Details are given in Feng's thesis (Ref. 2).

*c. Injection and extraction rates.*

Injection and extraction rates for the entire quantum well structure are determined by the transfer matrix for complex energies, applied across the whole structure. The complex energy poles of the transmission coefficient determine the total widths of the quasi-bound energy levels, which are related to the injection and extraction rates.

Details are given in Feng's thesis (Ref. 2).

## 3. Comparison of theory and experiments

Quantitative comparison of our theoretical predictions with experiments on various structures grown in Vienna have been carried out. Details are in Feng's Thesis (Ref. 2).

For I-V characteristics, we showed that the best way to compare the theory and experiment is to plot dV/dJ vs J, where J is the current density, and V the applied bias. We obtained very good agreement for all the structures (g428, g494, g534). We discovered that the internal population in these quantum well structures is more accurately described as a mixture of quantized and continuum states. We see this to be the result of a thin entry

barrier. To achieve a stronger quantization, we designed new structures with thicker entry barriers (g595, g596), and also obtained good agreement.

The plasma modes for all the structures were calculated, and an overall agreement with the emission spectrum was achieved. The newer structures had reduced line widths, as expected. Even for the newer structures, the line width was quite large (HWHM ~ 2.5 meV). Since our calculated maximum growth rates were 1 – 1.5 meV, these structures would not create a net plasma instability, only the line width will be reduced in the domain of the intrinsic instability.

Another type of structure was designed, where pure quantized states are obtained in a specially designed deeper potential pocket (g564). This structure produces a very sharp emission line (HWHM ~ 0.1 meV). We discuss this below, as topic 4.

4. Sharp Emission

The recently designed g564 is a 10 cascade structure, and each unit has a deep pocket created by InGaAs. The experimental results obtained by a step-scan, high resolution spectrometer for emission from this structure are very promising. A very sharp line is seen near 15 meV. The line width, as indicated by HWHM is ~ 0.1 meV. This strongly suggests, that we are very close to the onset of the plasma instability. This line disappears at T > 50 K, proving that this is not an artifact of some external, instrumental factors. Another broader line (HWHM ~ 0.5 meV) is also seen. Our energy calculations show these lines to be related to inter-subband separations.

5. Effects of magnetic field on scattering rates in quantum wells.

*(a) Electron-electron scattering.*

We extended the calculations for inter-subband relaxation processes due to the electron-electron scattering in a quantum well structure, to include a magnetic field. We find that the scattering rate is peaked at two possible sets of arrangements of the Landau levels (LL) of the two subbands of interest. The first set occurs when the LL of both subbands align, and the other set occurs when the LL of one subband lie exactly in the middle between the LL of the other subband. Importance of this phenomenon is twofold: (1) the reduction in the phase space leads to reduced inter-subband transport for certain ranges of the applied magnetic field, effectively reducing the electron-electron collision effect. This reduction improves the prospects for observing a plasma instability, when a magnetic field is applied.

(2) This result also provides a diagnostic tool for the relative strength of the two-electron scattering process versus one-electron processes such as electron-phonon and electron-surface roughness scatterings. Specific quantum well structures were designed, grown, and I-V characterized to confirm this result. Papers were published in Phys. Rev. Letters (Ref. 5) and Phys. Rev. B (Ref. 6).

*(b) Electron-LO phonon scattering.*

We also developed a formalism for electron-LO phonon scattering in the presence of a magnetic field. The above mentioned LL quantization produces periodic variation in the I-V results, due to corresponding variation in inter-subband electron-LO phonon scattering. An experiment was carried out on a quantum well structure in high magnetic field, and such oscillations were observed. A paper is under preparation.

6. New Experimental Connection

We have begun an interaction with an experimental group at the University of California at Santa Barbara (UCSB), to obtain an independent proof of principle of the plasma instability phenomenon in a terahertz pumped quantum well structure. UCSB has a free electron laser THz source (up to 5 THz). This can be used to generate the desired population inversion for our plasma instability scenario, without resorting to carrier injection and extraction by an applied bias. We have already designed a double quantum well suitable to realize this phenomenon. Work has begun at UCSB to experimentally test this idea.

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3. K. Kempa , P. Bakshi J. Engelbrecht and Y. Zhou, "Inter-subband Relaxation due to Electron-electron Scattering in Quantum Well Structures", Physica E, 7, 225-228 (2000).
4. K. Kempa, P. Bakshi J. Engelbrecht and Y. Zhou, "Intersubband Electron Transitions due to electron-electron interactions in Quantum Well Structures", Phys. Rev. B 61, 11083-11087 (2000).

5. K. Kempa, Y. Zhou, J. Engelbrecht, P. Bakshi, H. Ha, J. Moser, M. Naughton, J. Ulrich, G. strasser, E. Gornik and K. Unterrainer "Intersubband Transport in Quantum Wells in strong magnetic fields mediated by single-and two-electron processes", Phys. Rev. Letters, 88, 226803, (2002).
6. K. Kempa, Y. Zhou, J. R. Engelbrecht, and P. Bakshi, "Electron-electron scattering in strong magnetic fields in quantum well systems", Physical Review B 68, 085032 (2003)

## IV. Publications.

*a) Publication (peer reviewed journals)*

1. P. Bakshi and K. Kempa, "Inter-subband Plasmon Emission based THz Lasers", Physica E 7, 63-68 (2000).
2. K. Kempa , P. Bakshi J. Engelbrecht and Y. Zhou, "Inter-subband Relaxation due to Electron-electron Scattering in Quantum Well Structures", Physica E, 7, 225-228 (2000).
3. K. Kempa, P. Bakshi J. Engelbrecht and Y. Zhou, "Intersubband Electron Transitions due to electron-electron interactions in Quantum Well Structures", Phys. Rev. B 61, 11083-11087 (2000).
4. K. Kempa, Y. Zhou, J. Engelbrecht, P. Bakshi, H. Ha, J. Moser, M. Naughton, J. Ulrich, G. strasser, E. Gornik and K. Unterrainer "Intersubband Transport in Quantum Wells in strong magnetic fields mediated by single-and two-electron processes", Phys. Rev. Letters, 88, 226803, (2002).
5. K. Kempa, Y. Zhou, J. R. Engelbrecht, and P. Bakshi, "Electron-electron scattering in strong magnetic fields in quantum well systems", Physical Review B 68, 085032 (2003).

*b) Papers presented at APS March Meetings.*

1. P. Bakshi, C. Du, G. Feng, K. Kempa, "Transport and Response for current driven non-equilibrium steady state complex quantum well structures". Bull. Amer. Phys. Soc. 46, 740, (2001).
2. K. Kempa, P. Bakshi, Y. Zhao, J. Engelbrecht, "Effects of magnetic field on electron-electron intersaubband scattering rates in quantum wells", Bull. Amer. Phys. Soc. 46, 741, (2001).

3. P. Bakshi, K. Kempa, C. Du, G. Feng, "Quantum well structures for THz radiation: theory of non-equilibrium transport". Bull. Amer. Phys. Soc. 47, 283, (2002).
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c) *Invited papers at conferences, which had no proceedings*

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2. K. Kempa, P. Bakshi, Y. Zhao, J. Engelbrecht, "Effects of magnetic field on electron-electron intersaubband scattering rates in quantum wells", at the International Terahertz Workshop 2000, Sandbjerg Castle, Denmark, September 2000.
3. P. Bakshi, G. Feng, C. Du, K. Kempa, "Towards THz radiation sources via intersubband plasma instabilities"at the 6th International Conference on Intersubband Transitions in Quantum Wells, ITQW 2001, Asilomar, CA, September 2001.
4. K. Kempa, P. Bakshi, Y. Zhao, J. Engelbrecht, "Transport signatures of the two-electron inter-landau level scattering", at the 6th International Conference on Intersubband Transitions in Quantum Wells, ITQW 2001, Asilomar, CA, September 2001.

d) *PhD Thesis.*

1. G. Feng, "Transport and Response Properties of non-equilibrium Steady State Semiconductor Quantum Well Structures", Ph.D Thesis, Boston College (2002).

## V. Personnel.

1. Prof. P. Bakshi (Faculty), Principal Investigator.
2. Prof. K. Kempa (Faculty), Principal Investigator.
3. Dr. C. Du, Senior Research Scientist.
4. G. Feng (Graduate Student), Research Assistant, Ph.D. degree completed in 2002.